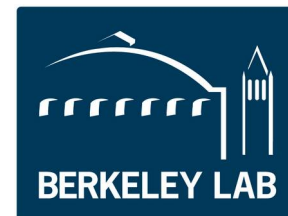
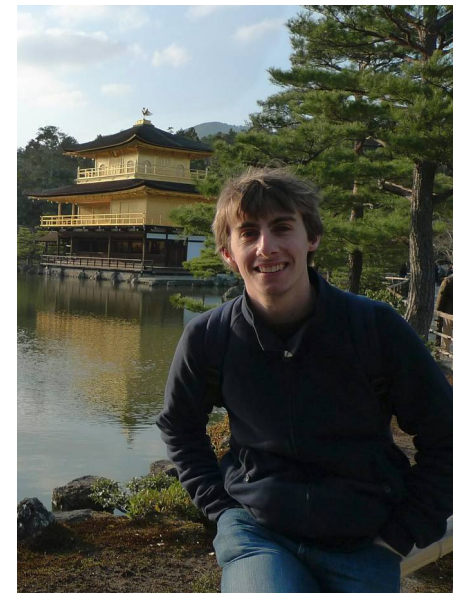


DUNE long-baseline oscillation physics sensitivity

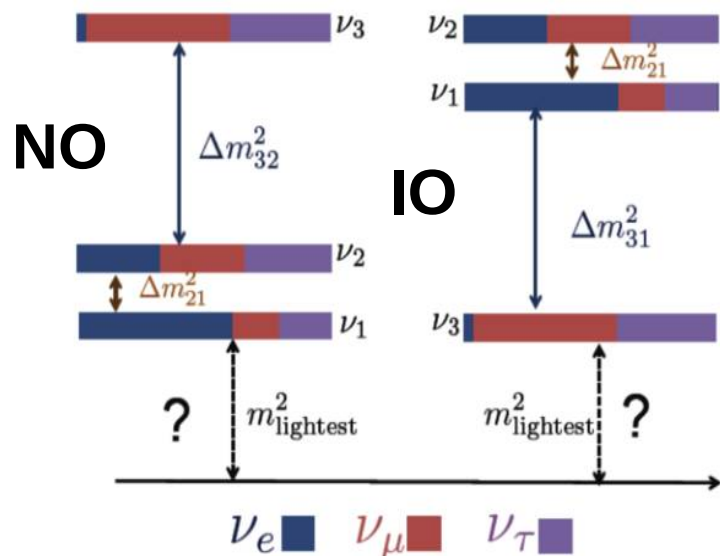
Callum Wilkinson

Lawrence Berkeley National Laboratory

NuFact 2022, 5th August 2022



Open questions in neutrino physics



Two mass scales

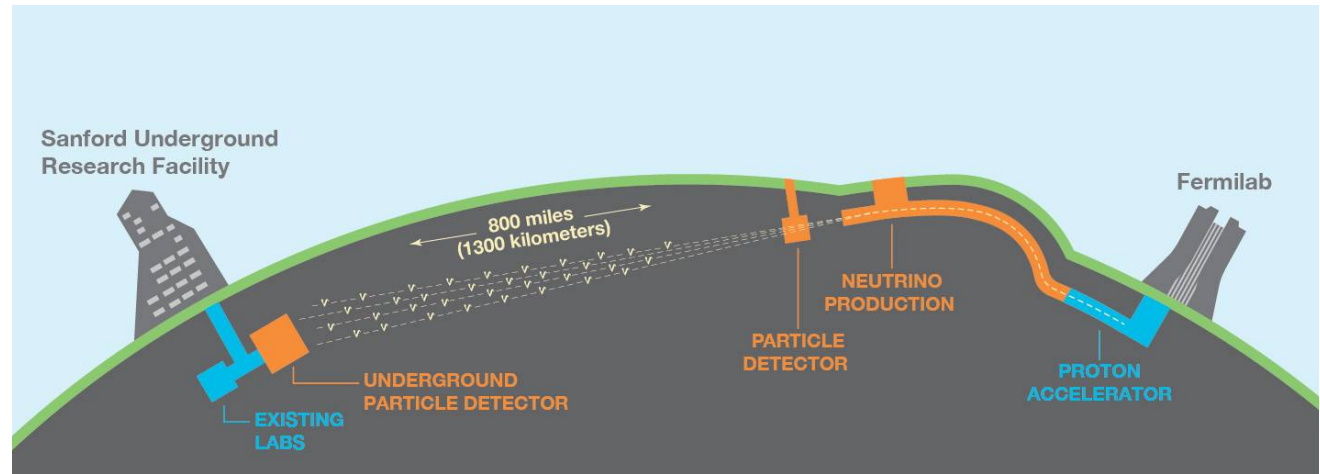
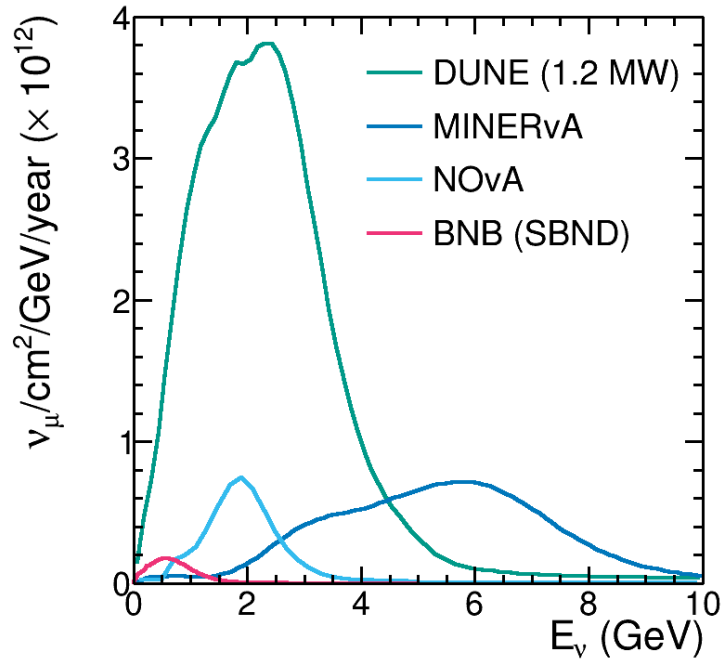
$$|\Delta m^2| \sim 2 \times 10^{-3} \text{ eV}^2$$

$$\Delta m_{21}^2 \sim 7 \times 10^{-5} \text{ eV}^2$$

- What is the neutrino mass ordering?
- Is there leptonic CP violation?
- Is this picture complete? E.g. >3 flavors? Non-unitary U_{PMNS} , ...
- Connected to many interesting theoretical questions

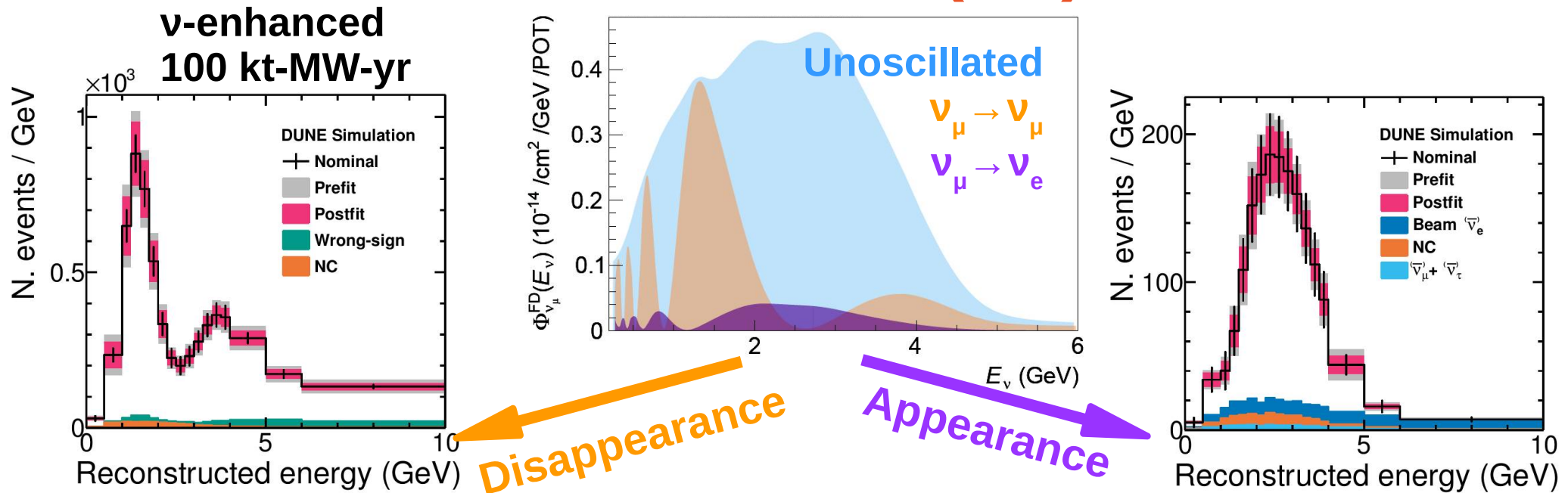
$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\text{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

DUNE

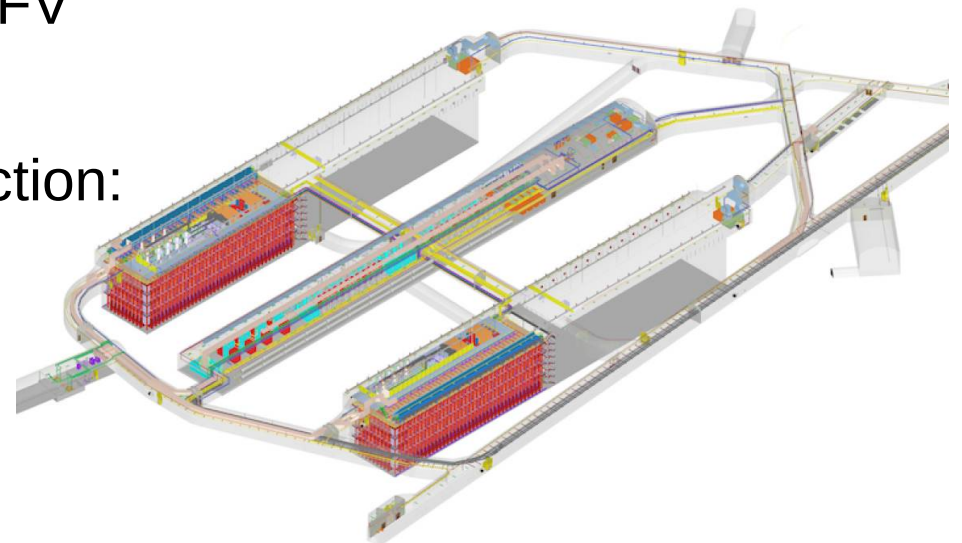


- $L \approx 1285 \text{ km}$; $E_\nu \approx 2.5 \text{ GeV}$ (*broad band*); liquid argon time projection chamber (LArTPC)
- Unprecedented intensity neutrino beam ($1.2 \rightarrow 2.4 \text{ MW}$)
- Near detector system at Fermilab
- 4 x 17 kt far detector modules at SURF

Far Detector (FD)



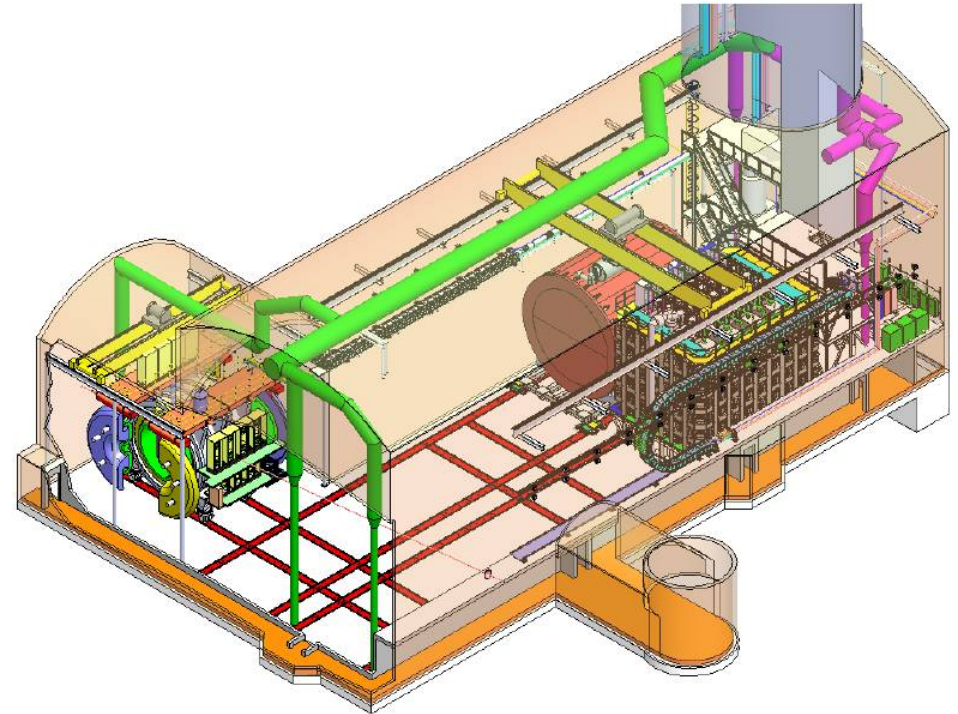
- 4 x 17 kt modules, minimum 10 kt FV each (initial 2 x LAr)
- Full FD1 simulation and reconstruction: [PRD102, 092003 \(2020\)](#)
- Four samples in analysis: ν_μ & ν_e in ν and $\bar{\nu}$ enhanced modes



Near Detector (ND)

Core requirements:

- Constrain neutrino flux
- Constrain $\nu/\bar{\nu}$ -Ar interactions
- Exceed FD energy resolutions
- Tolerate high rate environment



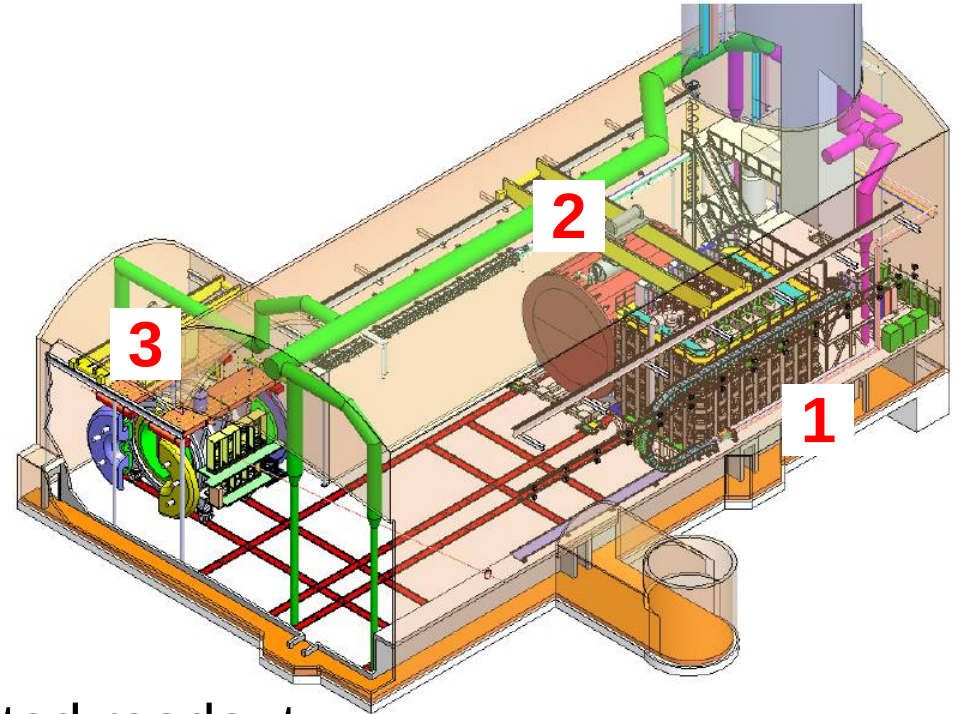
Near Detector (ND)

Core requirements:

- Constrain neutrino flux
- Constrain $\nu/\bar{\nu}$ -Ar interactions
- Exceed FD energy resolutions
- Tolerate high rate environment

Three major components:

- 1** - Core 150 t LArTPC with pixelated readout
- 2** - Downstream magnetized tracker
- 3** - SAND: dedicated beam monitor



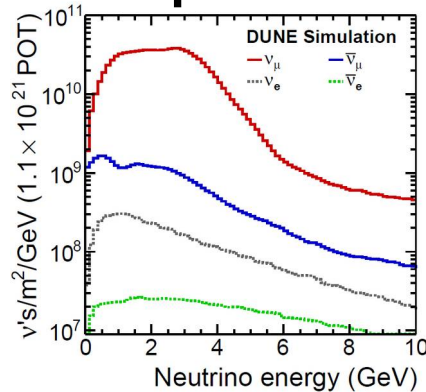
See [J. Wolcott's talk](#)

ND CDR: [Instruments 2021, 5\(4\), 31](#)

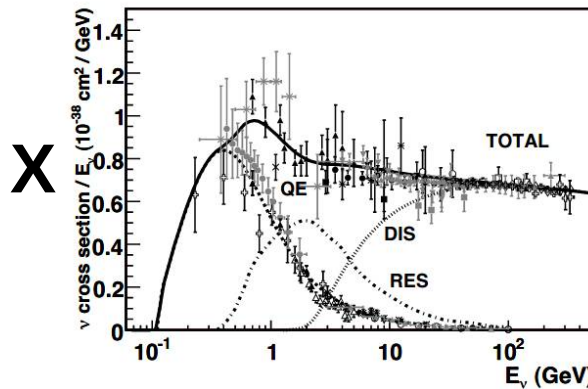
See [Z. Vallari's talk](#)

Analysis summary

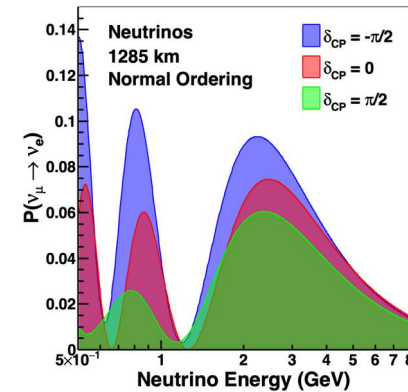
Flux prediction



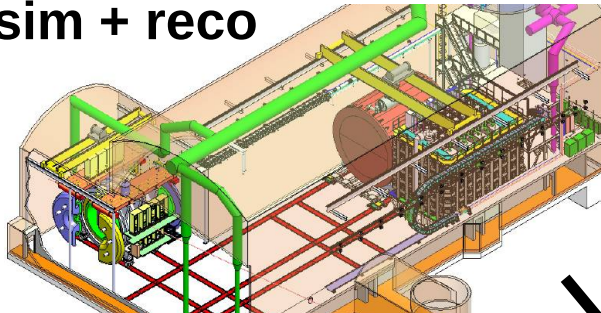
Interaction model



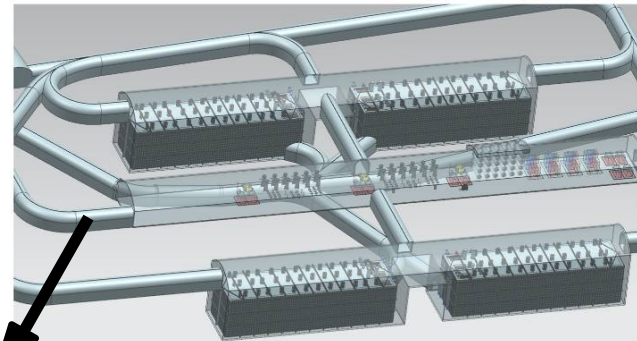
Oscillations



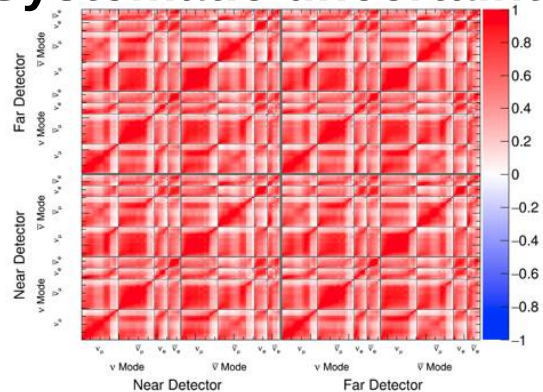
ND sim + reco



FD sim + reco



Systematic uncertainties



Fitting framework

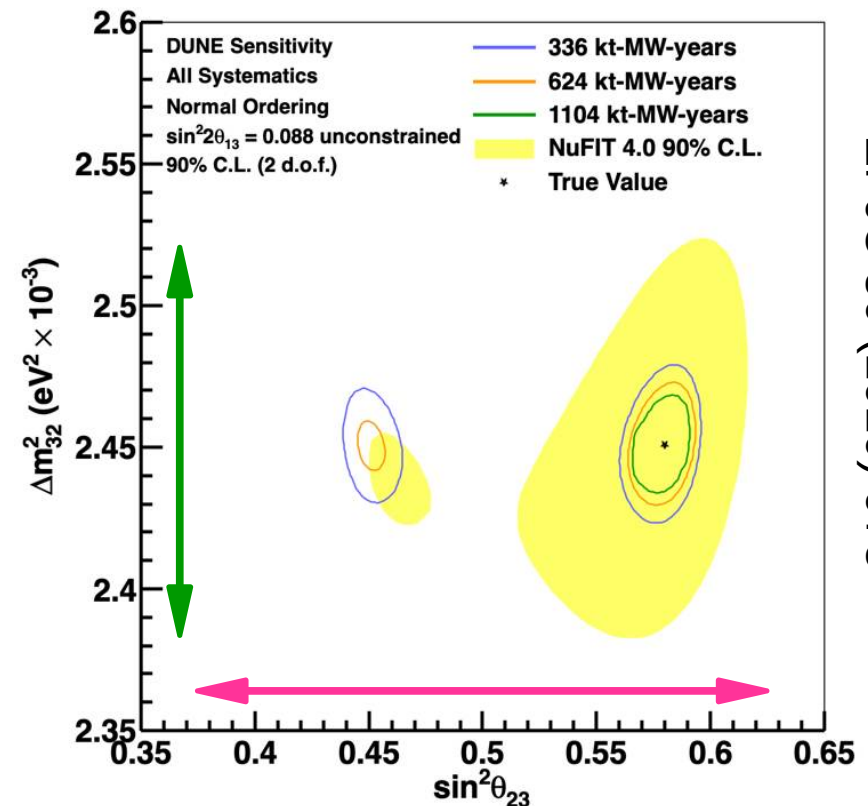
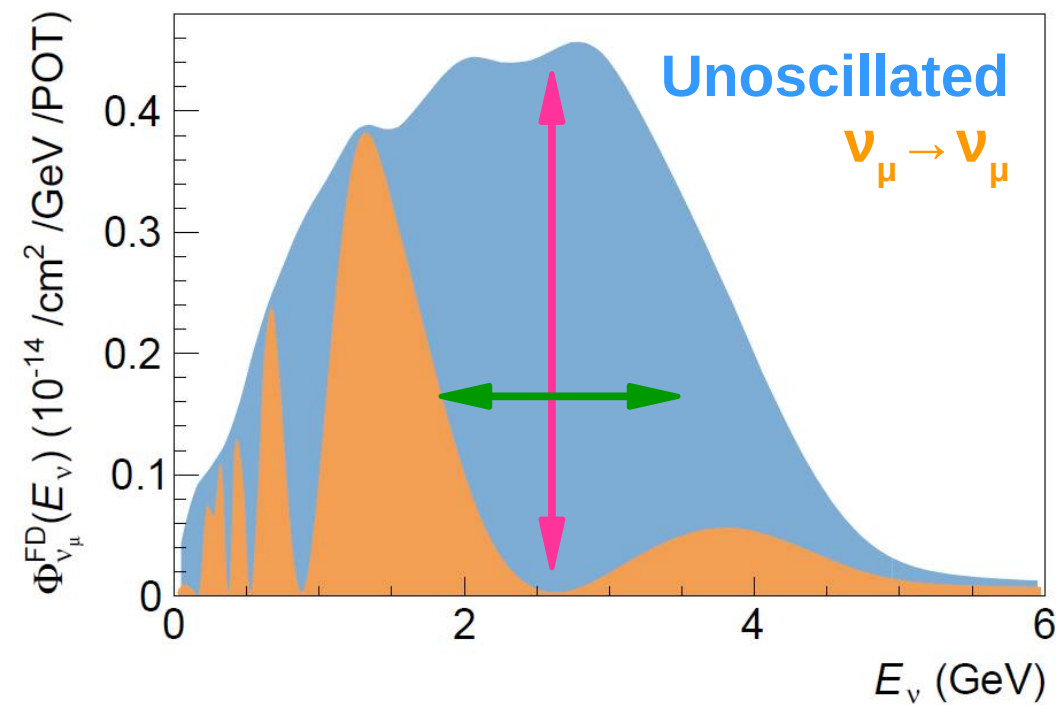
$$\chi^2(\vec{\vartheta}, \vec{x}) = 2 \sum_i^{N_{\text{bins}}} \left[M_i(\vec{\vartheta}, \vec{x}) - D_i + D_i \ln \left(\frac{D_i}{M_i(\vec{\vartheta}, \vec{x})} \right) \right] + \sum_j^{N_{\text{systs}}} \left[\frac{\Delta x_j}{\sigma_j} \right]^2$$

Muon (anti)neutrino disappearance

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) = 1 - \underbrace{(\cos^4 \theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23})}_{\text{pink bar}} \underbrace{\sin^2 \Phi_{32}}_{\text{green bar}} + \dots$$

$$\Phi_{ji} = \frac{1.27 \Delta m_{ji}^2 L}{E_\nu}$$

90% confidence



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Electron (anti)neutrino appearance

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Phi_{31} - aL)}{(\Phi_{31} - aL)^2} \Phi_{31}^2$$

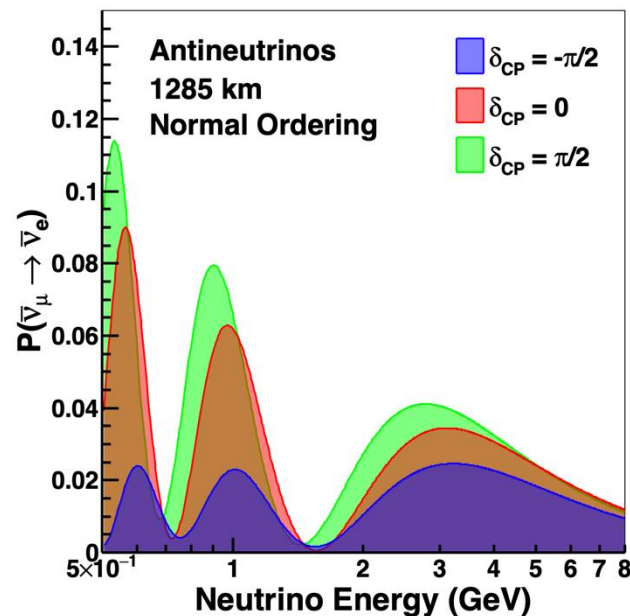
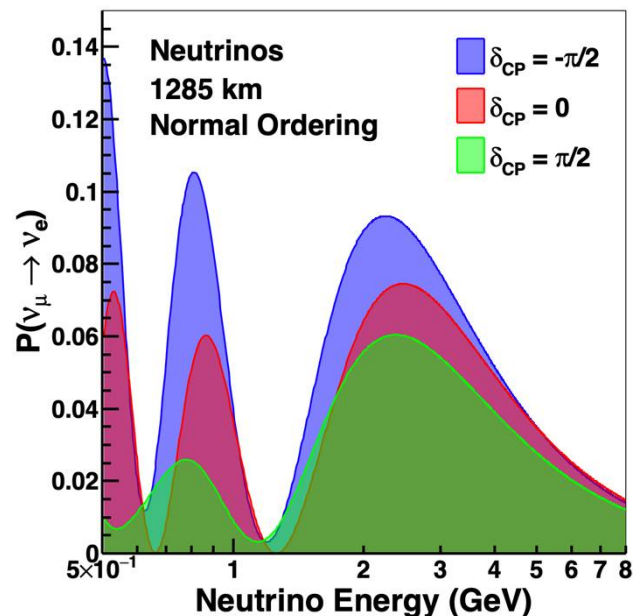
$$+ \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Phi_{31} - aL)}{(\Phi_{31} - aL)} \Phi_{31} \frac{\sin(aL)}{(aL)} \Phi_{21} \cos(\Phi_{31} \pm \delta_{CP})$$

$$+ \dots$$

Sign change
for ν_e and $\bar{\nu}_e$

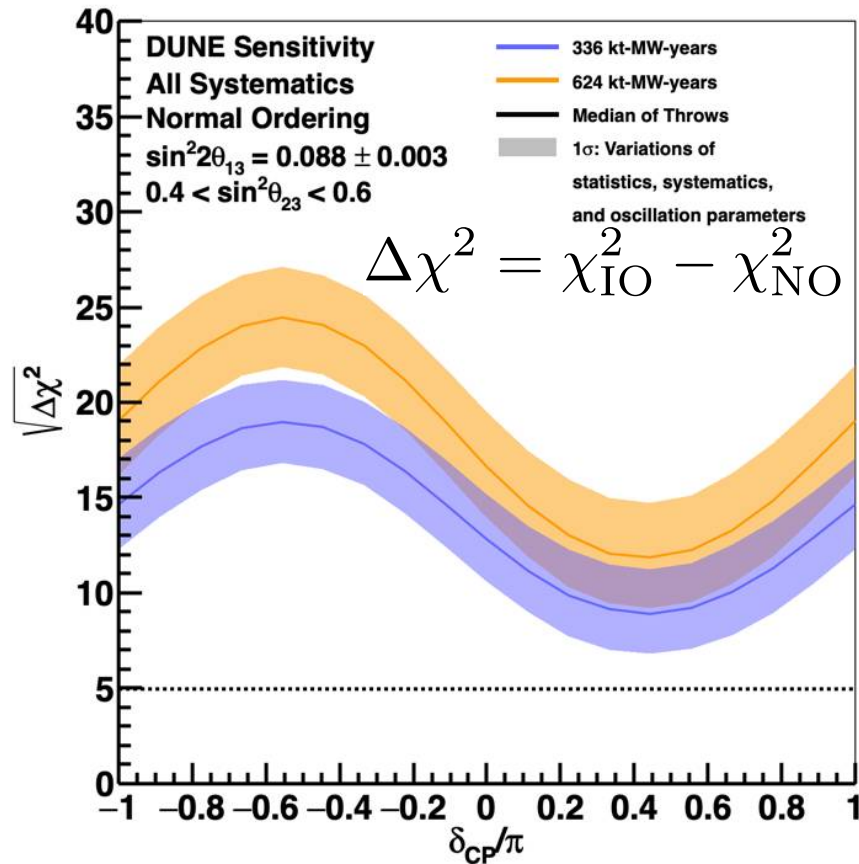
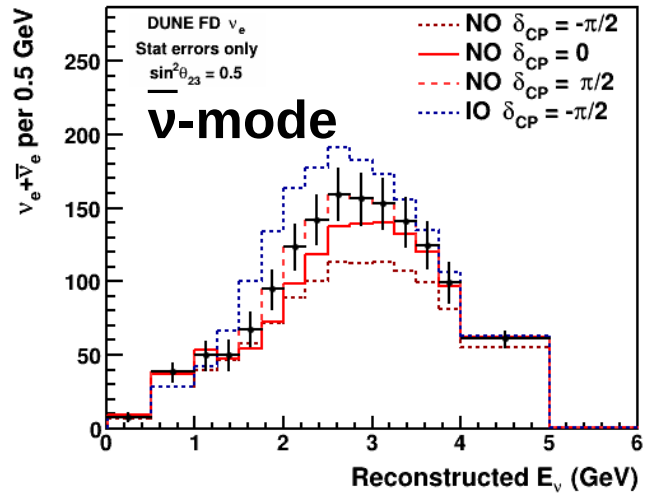
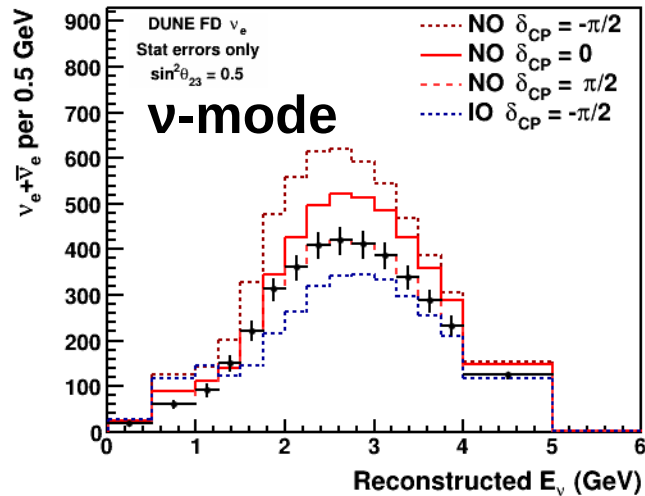
$$\Phi_{ji} = \frac{1.27 \Delta m_{ji}^2 L}{E_\nu} \quad a = \pm \frac{G_F N_e}{\sqrt{2}}$$

Interplay between
mass ordering
and CP-phase



Spectral
measurement
allows DUNE to
disentangle effects

MO sensitivity

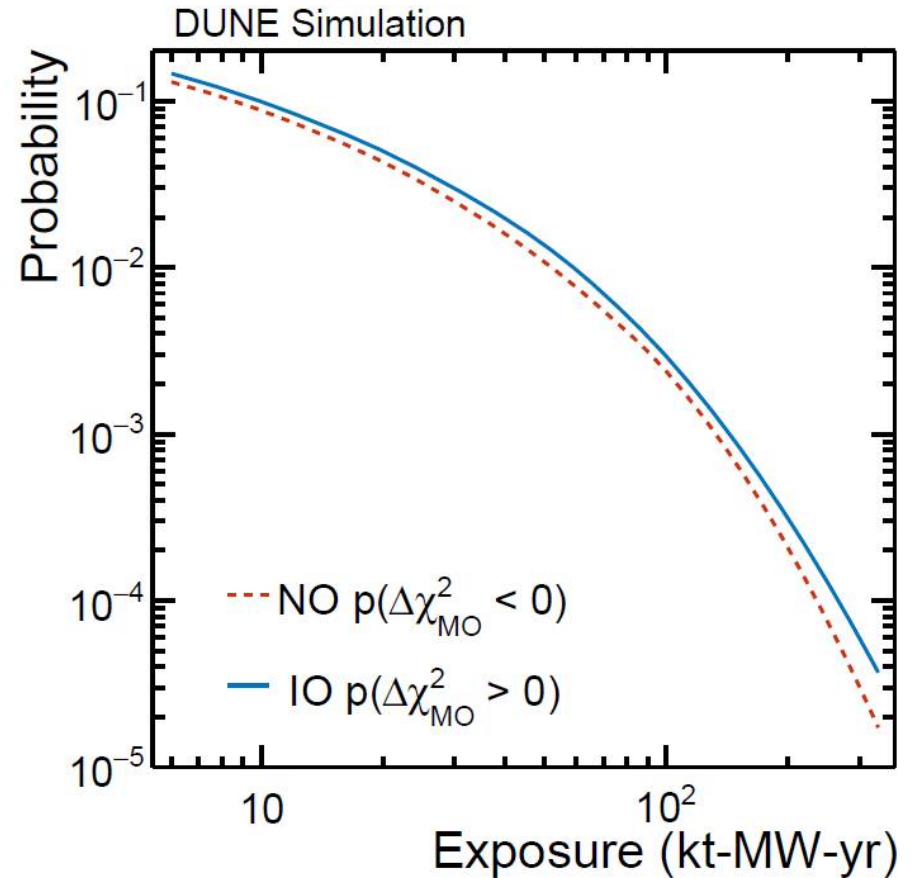
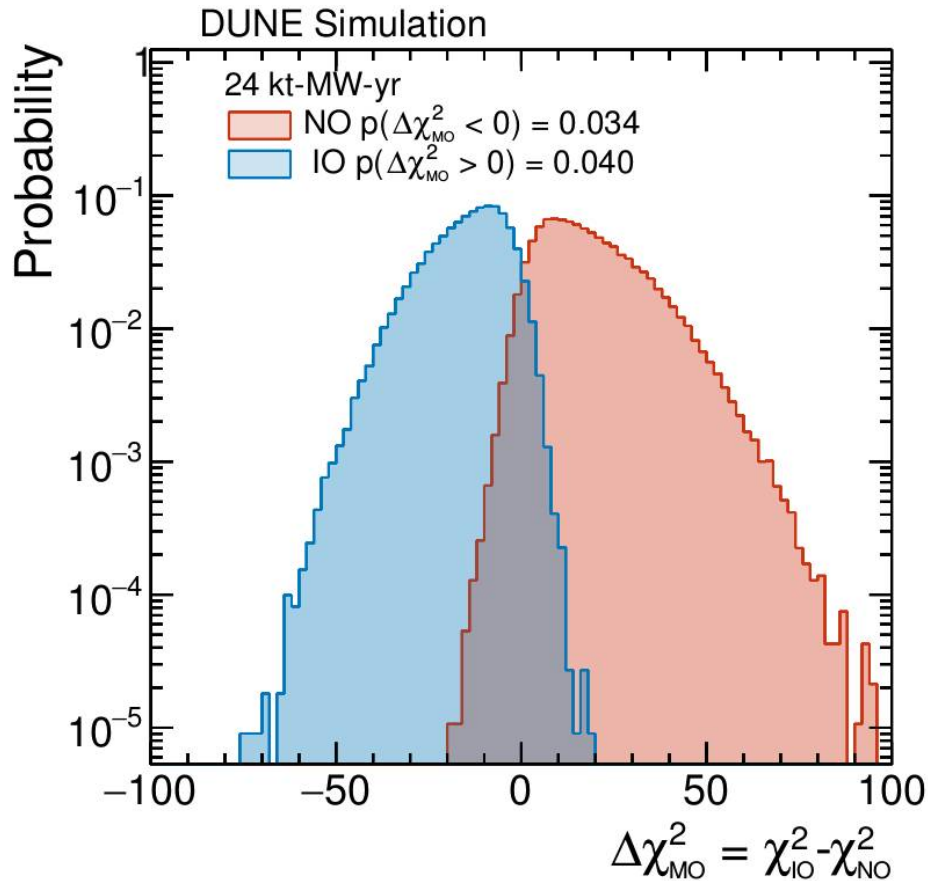


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Unrivaled ability to resolve the mass ordering:

- Regardless of other parameter values
- Without reliance on other oscillation parameter inputs

MO sensitivity

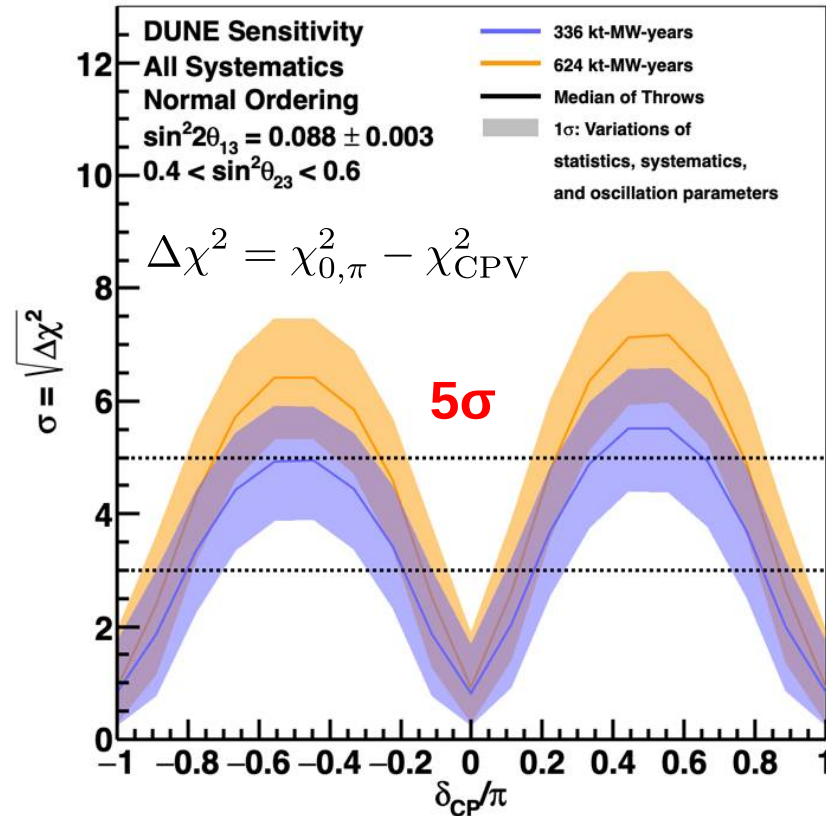
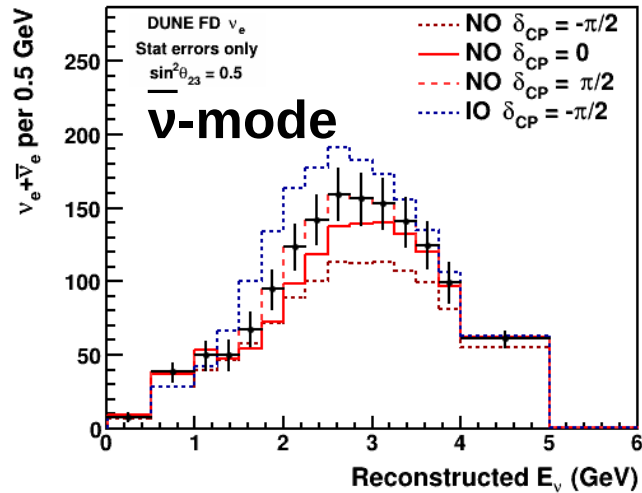
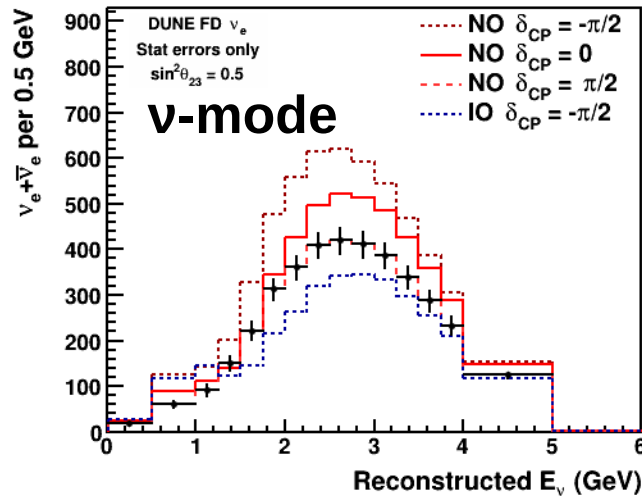


PRD 105 (2022) 7, 072006

Strong MO potential with short exposures

Probability < 0.01 to prefer the wrong neutrino mass ordering after 66 kt-MW-yr

CPV sensitivity

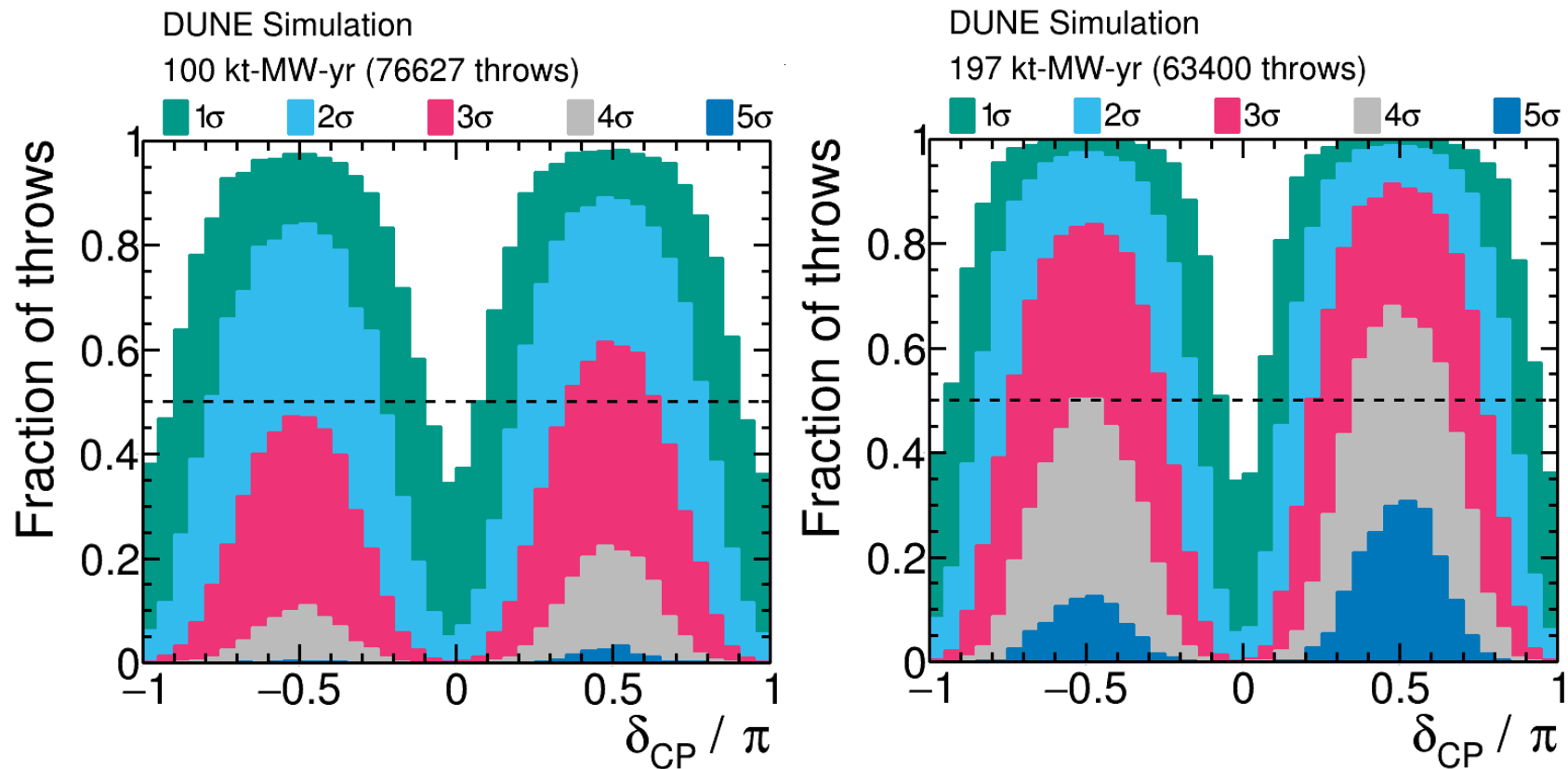


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>5 σ discovery potential for >50% of δ_{CP} values

No prior knowledge of other oscillation parameters needed

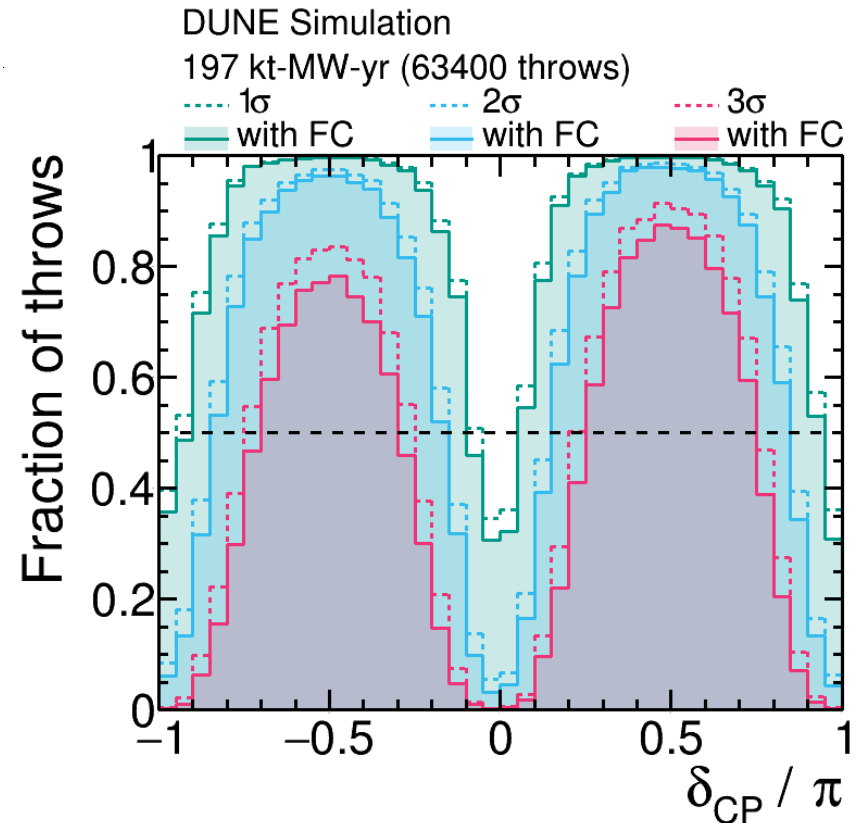
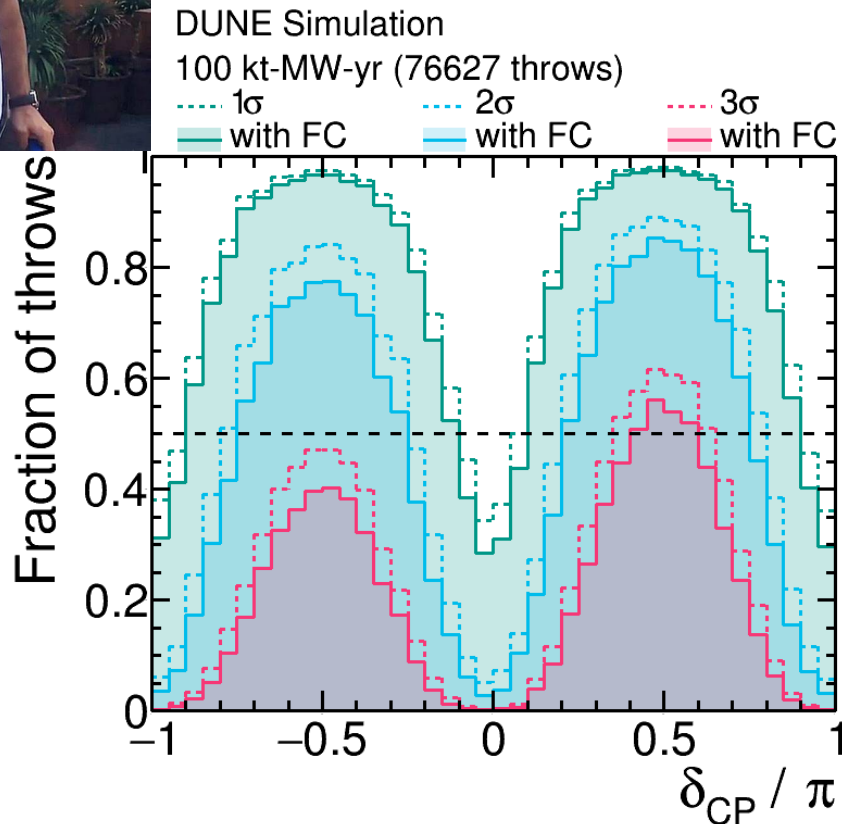
CPV sensitivity



PRD 105 (2022) 7, 072006

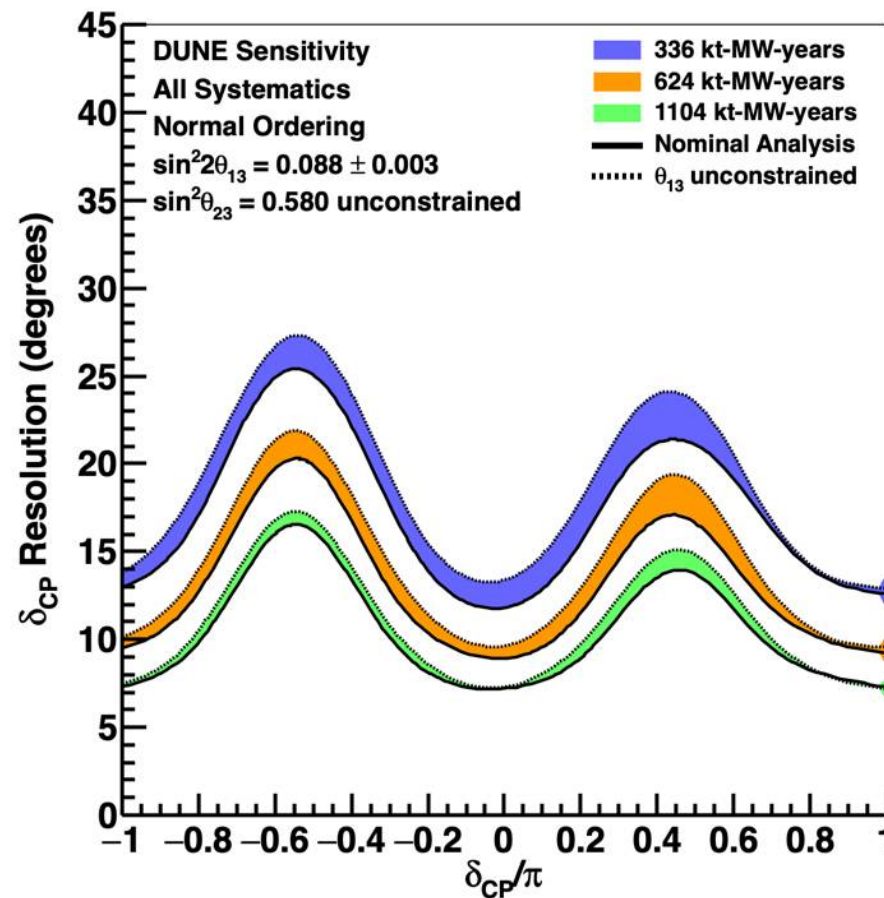
Syst.+stat. throws exceeding 1-5 σ significance thresholds
 ≈ 100 kt-MW-yr, 3 σ at maximal δ_{CP}
 ≈ 200 kt-MW-yr, 3 σ for 50% of δ_{CP} values

A sprinkle more statistical rigor



FC corrections don't change the picture
(Computationally prohibitive above 3 σ)

δ_{CP} resolution

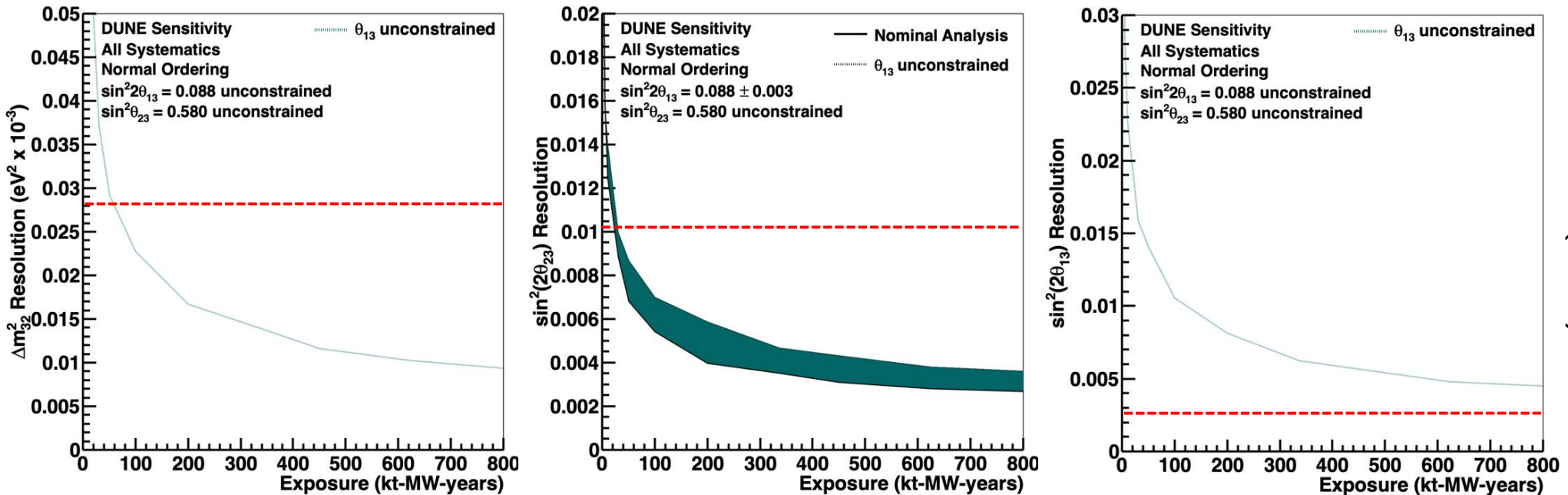


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7–16° δ_{CP} resolution **regardless of true value**

Not just CPV!

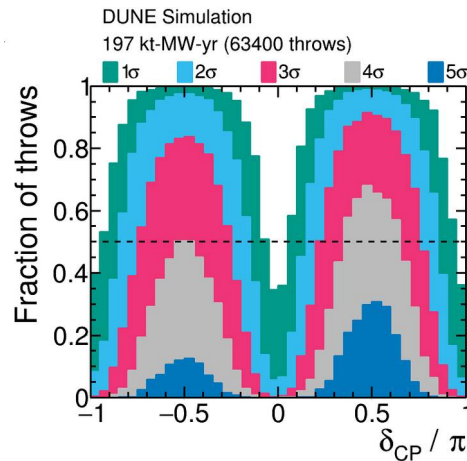
DUNE precision measurements



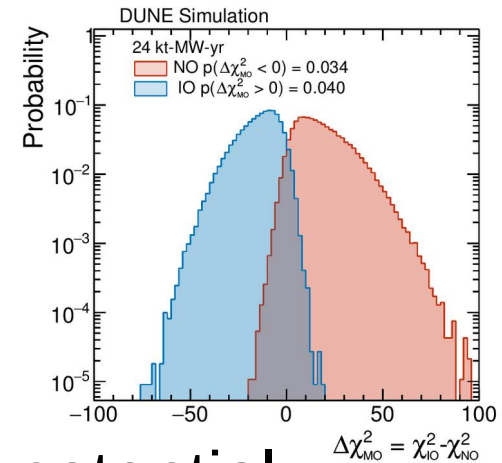
- Expected DUNE resolution vs exposure and **current global fit** (NuFit 5.0: JHEP 09 (2020) 178)
- Ultimate sensitivity approaches reactor θ_{13}
- Constrain δ_{CP} , Δm_{32}^2 , θ_{23} , θ_{13} and MO with a single experiment

DUNE oscillation summary

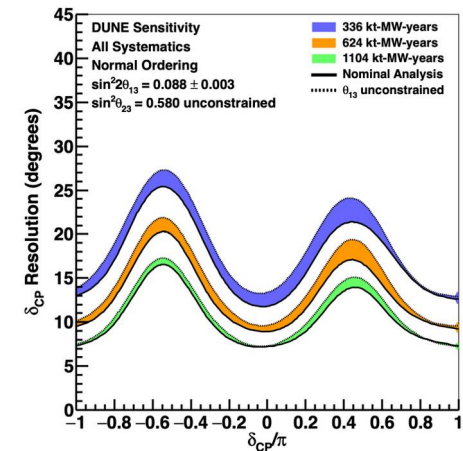
Unambiguous MO measurement



Strong CPV discovery potential

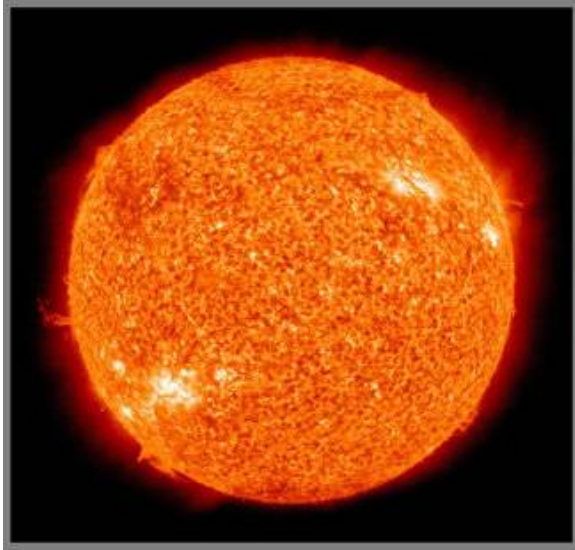


Precision osc. parameter measurements



Broad spectral measurements will stress test the U_{PMNS} model – is anything missing?

Part of a broader physics program!



Credit: Higgstan

